Anomalous Thermopower in the Metalliclike Phase of a 2D Hole System

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We report very low temperature (T) thermopower and resistivity (ρ) measurements on variable-density, two-dimensional hole systems confined to GaAs quantum wells. As the hole density is lowered from 1.49×10^{11} cm^{-2} to 0.14×10^{11} cm^{-2}, the system crosses from an insulating ($\frac{d\rho}{dT} \lesssim 0$) to a metallic regime ($\frac{d\rho}{dT} > 0$) and finally displays insulating behavior ($\frac{d\rho}{dT} < 0$). Diffusion thermopower shows a striking sign reversal in a narrow range of density in the metallic regime, suggesting a qualitative change in the conduction or the scattering mechanism.

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In a seminal work, Abrahams *et al.* [1] showed that, at zero temperature, there should be no genuine metallic phase for a noninteracting two-dimensional (2D) carrier system with a finite amount of disorder. However, recently, the observation of metallic behavior at low temperature T and zero magnetic field in n-Si metal-oxide-semiconductor field-effect transistors (MOSFETs) [2–4] gave impetus for several resistivity studies [5–9] and theoretical work [10–12] in various 2D systems. In particular, an intriguing metallic behavior has been evidenced experimentally in GaAs-based 2D hole systems (2DHSs) [6–9]. The experiments revealed remarkable changes in the T dependence of the resistivity ρ as the hole density p is varied. Starting from low densities, ρ at low T exceeds h/e^2 and shows an insulating behavior, which is characteristic of a mobility gap [6,7]. Increasing the carrier density causes a crossover to a mixed behavior in which ρ displays a nonmonotonous T dependence [9]. The most striking behavior is observed at slightly higher p, where a metallic behavior ($\frac{d\rho}{dT} > 0$) persists down to the lowest accessible temperatures [6,7]. In that density range, the resistivity diminishes by a factor of about 2 as T is reduced below ≈1 K. At even higher p, the resistivity enters a second insulating regime characterized by a small increase of ρ at very low temperature [7,13].

The metalliclike phase fueled a debate on the possibility of a metal-insulator transition (MIT) in 2DHSs. Dobrosavljević *et al.* [10], using a scaling analysis which takes into account interactions, suggested that the observed metallic behavior could be that of a non-Fermi liquid. By examining the microscopic mechanisms of scattering, Altshuler and Maslov [11] proposed a simple model that explains the exponential drop in ρ at low T, which characterizes the metallic regime. Very recently, the finite T properties of the apparent 2D metallic phase found a possible explanation in terms of screening, impurity, and phonon scattering effects [12].

Up to now, the resistivity has been by far the main tool to characterize the apparent MIT in 2D carrier systems. Despite the considerable body of experimental evidence accumulated, a thorough and consensual understanding of the 2D metalliclike phase is still missing, partly due to the lack of information on other physical properties. While scattering is central to some of the proposed explanations, the resistivity is of limited help to distinguish between different scattering mechanisms. By contrast, thermopower is a very sensitive probe of single and many body properties of the 2D systems [14–17] and is usually complementary to resistivity. For example, diffusion thermopower has opposite T dependencies for a mobility gap than for a real (energy) gap, while resistivity shows an insulating behavior in both cases [17]. Of particular interest in the study of the MIT in 2D systems, diffusion thermopower is expected to provide valuable insight into the nature of conduction and scattering mechanisms. In this Letter we report measurements of the longitudinal thermopower S and resistivity, down to very low temperature, of a 2DHS exhibiting the metallic behavior. While phonon-drag thermopower does not show any peculiar behavior, diffusion thermopower exhibits a striking change of sign which is indicative of a qualitative difference in the scattering or the conduction mechanism.

The experiments were performed on two Si modulation doped GaAs/Al$_{0.3}$Ga$_{0.7}$As quantum wells, 200 Å wide, grown on (311)A GaAs substrates by molecular-beam epitaxy. Measurements were done on rectangular 7×2 mm^2 pieces cut along the $[\bar{2}33]$ (sample 1) and the $[01\bar{1}]$ (sample 2) directions with In(5% Zn) Ohmic contacts deposited on the edges parallel to the length of the sample. Resistivity was measured on sample 1 using van der Pauw geometry with current and voltage contacts along the $[\bar{2}33]$ direction. To measure thermopower, the samples were glued at one end to the cold finger of a dilution refrigerator using General Electric varnish. A strain gauge was glued at the other end of the samples and served as a heater to generate a T gradient along the specimens, which was kept below 10% of the mean T. The T difference along each sample was probed by two carbon paint resistors deposited on the top side of the heterostructures. Sample 1 had metal front and back gates that allowed tuning of the 2D hole density from 1.49 to 0.14×10^{11} cm^{-2}. Sample 2 was photoexcited with infrared light at low temperature to tune the density from 1.3 to 0.8×10^{11} cm^{-2}. Thermopower was measured by applying a sine-wave current at frequency $f \approx 2$ Hz through the heater and measuring the voltage induced along the sample at frequency $2f$ with a lock-in amplifier [18]. All the data are taken in the absence of a magnetic field.

The evolution of ρ with temperature for sample 1 is shown in Fig. 1. Our $\rho(T)$ results in both metallic and insulating regimes are very similar to those observed in previous measurements [6–9]. We can identify four different regimes. At one extreme, $p = 0.14 \times 10^{11}$ cm^{-2}, $\rho > h/e^2$ and the sample is in the insulating regime ($\frac{d\rho}{dT} < 0$). For $0.15 \lesssim p \lesssim 0.25 \times 10^{11}$ cm^{-2}, a mixed behavior is observed: $\frac{d\rho}{dT} < 0$ at high T but at low temperature $\frac{d\rho}{dT} > 0$, indicative of a metallic behavior. In the density range $0.28 \lesssim p \lesssim 0.59 \times 10^{11}$ cm^{-2}, we find a metallic behavior characterized by a dramatic and monotonic drop in ρ as T is lowered. We fitted our $\rho(T)$ data at these densities, for $T \lesssim T_F/3$, to the empirical formula $\rho = \rho_0 + \rho_1 \exp(-T_0/T)$, where ρ_0, ρ_1, and T_0 are free fitting parameters and T_F is the Fermi temperature [4]. The extracted T_0 obeys a linear dependence on p, in agreement with previous studies [6]. The insulating behavior at high p is exemplified by the $\rho(T)$ traces for $0.86 \lesssim p \lesssim 1.49 \times 10^{11}$ cm^{-2}. In this density range, the resistivity increases by up to a few percent with decreasing temperature [13].

The evolution of the measured thermopower, S, with T for sample 1 is shown in Fig. 2. The most remarkable feature of this data is that, in some narrow range of density, S reverses sign and becomes negative at very low T. Before discussing the data in detail, we briefly recall the general predictions for thermopower in 2D carrier systems. Two mechanisms, namely, the diffusion and the phonon drag, contribute to thermopower [14]. The diffusion thermopower S^d is expressed in terms of the conductivity σ by the Cutler-Mott formula [19]

$$S^d = \frac{\pi^2 k_B^2 T}{3e} \left(\frac{d \ln \sigma}{dE} \right)_{E=E_F}, \tag{1}$$

where E is the hole energy and E_F is the Fermi energy. Assuming that the 2DHS is degenerate and the scattering time τ has a functional dependence of the energy of the form $\tau \propto E^\alpha$, Eq. (1) writes as [20]

$$S^d = \frac{\pi^2 k_B^2 T}{3eE_F} (1 + \alpha). \tag{2}$$

Equation (2) implies that $S^d \propto T$, provided that α depends only on the 2D hole density. As for the phonon-drag thermopower S^g, it is given by [14,16]

$$S^g = \frac{\kappa}{(p/L_z)ev^2} \frac{1}{\tau_{ph}}, \tag{3}$$

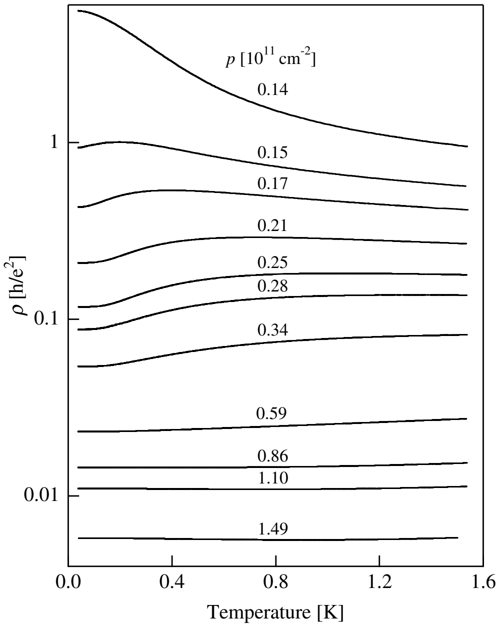

FIG. 1. Zero magnetic field T dependence of ρ measured for sample 1 at the indicated hole densities.

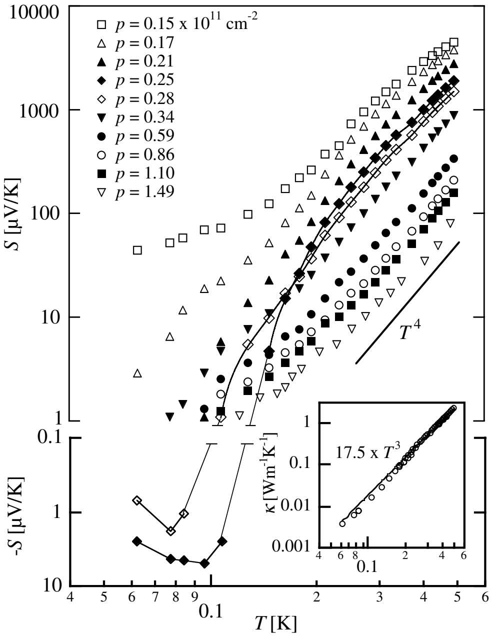

FIG. 2. Temperature dependence of S for the indicated hole densities. The solid curves are a guide for the eye. Inset: Thermal conductivity along the $[\bar{2}33]$ direction vs T. The solid line is a one-parameter fit (const $\times$ T^3) to the data points [22].

where κ is the thermal conductivity of the sample, L_z is the sample thickness in the confinement direction, $v = 3300\ \mathrm{ms}^{-1}$ is an appropriate average speed of sound in GaAs [21], and τ_{ph} stands for the phonon momentum relaxation time due to scattering by 2D holes.

In the high-T range ($T \gtrsim 0.2$ K), the measured S is dominated by S^g and exhibits a strong power-law T dependence (Fig. 2). Based on Eq. (3) and the measured thermal conductivity of the sample [22], given in the inset in Fig. 2, the estimated τ_{ph}^{-1} is plotted in Fig. 3 vs T/T_{F}. While for high densities τ_{ph}^{-1} exhibits a linear T dependence, it goes through a maximum for low densities. This maximum corresponds to the enhancement of the hole-phonon interaction (Kohn anomaly) when the dominant phonon wave vector is equal to twice the Fermi wave vector (arrows in Fig. 3) [16]. For T below the Kohn anomaly, $\tau_{\mathrm{ph}}^{-1} \propto T$ and $S^g = \mathcal{A}T^4$, where $\mathcal{A}$ is determined at each density from Fig. 3 and Eq. (3). The diffusion thermopower, which is significant at very low T, is then obtained at each density as $S^d = S - \mathcal{A}T^4$ (Fig. 4). For densities down to $p \approx 0.34 \times 10^{11}\ \mathrm{cm}^{-2}$, S^d is small, positive, and decreases approximately linearly as $T \rightarrow 0$ [Fig. 4(a)]. As p is reduced from 0.28 to $0.21 \times 10^{11}\ \mathrm{cm}^{-2}$, S^d changes sign and becomes strongly negative [Fig. 4(b)]. At even lower densities ($p \lesssim 0.17 \times 10^{11}\ \mathrm{cm}^{-2}$), where a mixed behavior is observed in ρ vs T (Fig. 1), the low temperature ($T \lesssim T_{\mathrm{F}}/10$) diffusion thermopower is again positive [Fig. 4(c)]. This low-T behavior is most likely related to S^d entering the insulating regime ($\rho > h/e^2$), albeit, based on the present data, it is not possible to identify the origin of the insulating behavior [23].

We now turn to the discussion of the diffusion thermopower data. The main features of the present data are best illustrated by plotting S^d at 0.1 K vs p (Fig. 5). For high densities [Fig. 4(a)], S^d is small implying that $\alpha \approx -1$. This value of α is consistent with scattering from background impurities being the dominant mechanism [20]. Sample 2 gives similar results (Fig. 5). The observed negative S^d in a narrow density range where the sample exhibits a metallic behavior (Fig. 1) suggests that other scattering mechanisms should be considered. A change in sign of S^d has already been reported [24,25]. The sign reversal observed in a GaAs/AlGaAs heterojunction [25] was attributed to the onset of occupation of the second subband. As for Si inversion layers [24], it was related to an upturn in the density dependence of mobility, when surface roughness scattering becomes equally important to scattering from background impurities. It is possible that the S^d sign reversal we observe is related to one of these mechanisms. In our 2DHS, the spin-orbit interaction and inversion asymmetry lead to a spin splitting of the energy bands, meaning that the 2D holes occupy two spin-split subbands which in general have different effective masses and mobilities [8]. Also, we expect both interface roughness and ionized impurity scattering to play a role in transport coefficients of our 2DHSs [26]. On the other hand, in our samples, the measured mobility at all temperatures decreases monotonically with decreasing density with no particular feature in the metallic regime. Moreover, we observe that S^d deviates from the $S^d \propto T$ dependence expected from Eq. (2). It is therefore possible that the reentrant change in sign

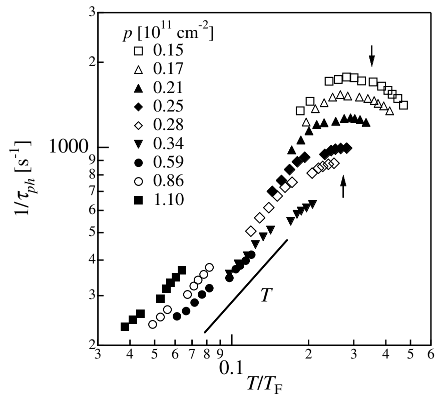

FIG. 3. τ_{ph}^{-1} vs T/T_{F} at various hole densities. The vertical arrows indicate the temperature where the Kohn anomaly is calculated for $p = 0.21 \times 10^{11}\ \mathrm{cm}^{-2}$ (bottom) and for $p = 0.15 \times 10^{11}\ \mathrm{cm}^{-2}$ (top) [16].

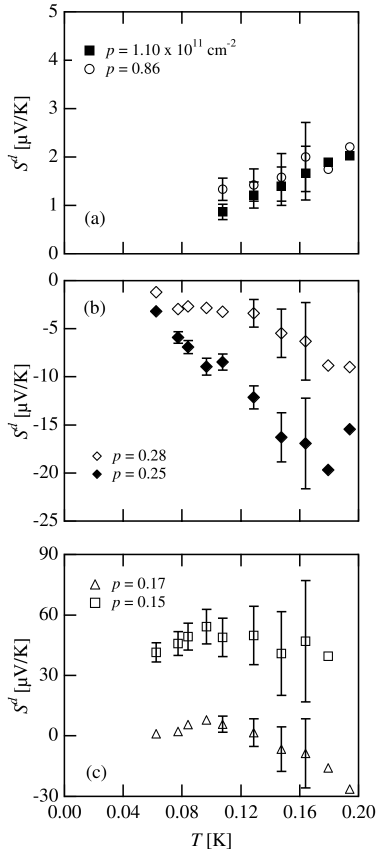

FIG. 4. $S^d = S - S^g$ vs T at the indicated hole densities. The error bar corresponds to ±10% uncertainty in both measured S and calculated S^g.

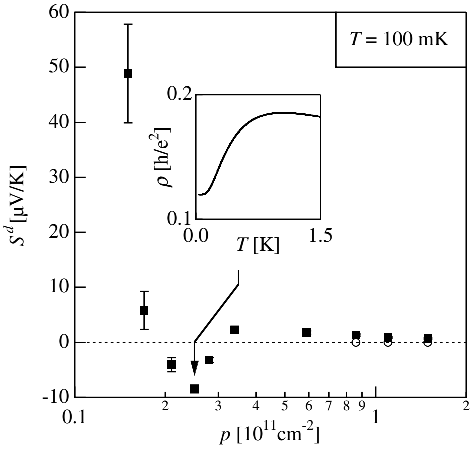

FIG. 5. $S^d = S - S^g$ vs p at $T = 0.1$ K. The full circles denote sample 1 data. The error bar corresponds to ±10% uncertainty in both measured S and calculated S^g. Sample 2 data are represented with open circles. The inset shows the T dependence of the resistivity for $p = 0.25 \times 10^{11}$ cm^{-2}.

of diffusion thermopower cannot be understood within the simple model for metallic S^d [Eq. (2)]. Given the peculiar exponential T dependence of ρ in the metallic regime, it is possible that the more general expression for S^d [Eq. (1)] should be used to interpret the data.

In summary, we have measured the low temperature resistivity and thermopower of variable density 2DHSs exhibiting metallic behavior at zero magnetic field. We found that diffusion thermopower shows an anomalous sign reversal in a narrow range of density in the metallic regime, suggesting a qualitative change in the conduction or the scattering mechanism.

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